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# HGQS02 Test Summary Report

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# Chapter 1

# General Overview

## 1.1 Test Summary Report Outline

This report presents preliminary results of HGQS02 testing at the FNAL Vertical Magnet Test Facility. HGQS02 is the second 70 mm-aperture, short R&D model LHC quadrupole built at FNAL.

The cold testing overview is presented in chapter 1.

Chapter 2 is devoted to quench performance tests. An overview of quench history is first given, followed by quench start locations. Relevant test conditions and results are given in summary tables.

Heater studies are presented in Chapter 3. Strip and spot heater induced quenches were performed at several different excitation currents and heater voltages at 1.9K. The time delay in quench initiation under these various conditions is presented as a function of the normalized current. We also measured the quench integral as a function of current and a cable segment tempreprature rise as a function of the quench integral.

Chapter 4 summarizes strain gauge (SG) runs performed throughout the test. Included here are summary sheets of all SG runs, and representative plots of coil stress and end force vs. $I^2$ (where I is the magnet excitation current) to the highest attainable current at each test temperature. Also included are tables summarizing SG readings at 0 A magnet excitation current (warm, before and after cool down), and plots of stress and end forces vs. time (summarizing SG history for the entire test).

RRR study is summarized in Chapter 5.

## 1.2 Test Overview

HGQS02 was tested according to the runplan attached as an Appendix to this note. The magnet was placed into the VMTF dewar and it was first cooled down on May 18, 1998, however cold testing began on May 28. The first test cycle ended June 12 with subsequent warm up to room temperature. The second test cycle started on June $27^{th}$ after cool down to 4.5K and ended on July $3^{rd}$ Between the two test cycles the magnet non-lead end preload was set to zero.

### 1.2.1 Test Cycle 1

Initial cooldown was to 4.5K without restriction on the differences between any of the temperature sensors located in the VMTF dewar. At 4.5K the first spontaneous quench of the magnet occurred at 7365A. Six additional quenches were made at the same 20A/sec ramp rate before proceeding with ramp to quench at 300A/sec. Next the magnet was cooled to 1.9K and strain gauge runs performed. The first 1.9K quench occurred at 9191A - quite low relative to the HGQS02 cable short sample limit. The magnet was quenched twenty-two additional times and then, given the slow training, we decided to do one more spontaneous quench at high ramp rate (300A/sec).

After magnetic measurements, heater studies were made at 1.9K. The magnet was quenched 20 times with various magnet excitation currents and dump delays.

In order to make correlations of "snapshot" events and magnet inductances we made a special run. The quench data logging frequency was changed to a slower rate (0.19Hz) and the magnet was ramped with 100A/sec to 11000A, but at 10665A a quench occured. The pentek data loggers were still recording snap shot data when the quench occured so quench data were not saved as a separate file. Due to the lack of high frequency recording of the data, the quench information is pretty poor.

We closed our first test cycle with quench current temperature dependence studies. The magnet was quenched at 3 different temperatures ranging from 1.9K to 2.1K.

During magnet warm up we performed 4 wire resistance measurements to obtain data for RRR studies.

### 1.2.2 Test Cycle 2

The magnet was cooled down to 4.5K and strain gauge runs were performed. The first quench of TC 2 occured at 9386 A. Six additional quenches were made: four of them at the same 20 A/sec ramp rate, and two more with higher ramp rates (300A/sec and 150A/sec). The magnet was cooled to 1.9K. Strain gauge runs were performed, and the first quench at 1.9K occurred at 9850A. The magnet was quenched five additional times. Six more heater induced quenches were performed and we warmed the magnet up 4.5K.

At 4.5K we quenched the magnet twice then EIEO measurements were performed.

# Chapter 2

# Quench behavior

This chapter summarizes the quench behavior of the magnet. Instrumentation settings for the HGQS02 test are summarized in Table 2.1 and Table 2.2; a detailed description of the instrumentation and its configuration is presented elsewhere.

Quench data acquisition was performed using the VMTF (pentek) readout system with binary quench data stored on a UNIX workstation. The location of the files are on MTF UNIX cluster:

/vmtf/data/Quench/vmtf.hgqs02/

The names of the quench files are summarized in Table 2.5 and 2.6. The data were analyzed using the quenchXmgr utility. HGQS02 had about 96 voltage taps, primarily instrumenting the pole turns and wedges on the four inner and outer coil quadrants and inner/outer coil splice regions.

## 2.1 Quench history

### 2.1.1 Test Cycle I

HGQS02 was tested according to the run plan attached as an Appendix to this note. The quench history is summarized in Table 2.3 and Table 2.4 and in Figure 2.1. Quench testing began at 4.5K at a ramp rate of 20A/s. The first spontaneous quench current was at 7365A, and the six additional quenches at 20A/s successively increased in quench current; the seventh quench reached 9203A. Since the predicted short sample limit of the superconducting cable used in this magnet is 10700kA, the quench current obtained is about 14% below that expected. The magnet was then ramped to quench at ramp rate of 300A/s (quench number 8).

The magnet was quenched 23 times (quench numbers 9-31) at 1.9K with the quench current monotonically increasing $\sim$ 100A -300A per quench. The ramp rate for these quenches was 20A/sec. As with 4.5K, the current at quench at 1.9K ceased to increase significantly even though it was twentysix hundred Amps below the predicted short sample limit of 14100A. Next, ramps to quench at 1.9K were performed at ramp rates of 160A/s, 300A/s, 100A/s, (quench numbers 32-34).

At the end of the first test cycle, 3 additional quenches were taken at temperatures ranging from 1.9K to 2.1K. The magnet was ramped to quench at 20A/sec.

### 2.1.2 Test Cycle II

The magnet underwent thermal cycle to 300K and was cooled back down to 4.5K. The magnet was quenched seven times at this temperature. The $38^{th}$ spontaneous quench current (first quench of the second test cycle) was at 9386 A. Since, the next four quench currents were also far below the short sample limit, we quenched the magnet twice more with different ramp rates (300A/sec and 150A/sec) and then we cooled the magnet to 1.9K. At 1.9K the magnet was quenched 6 times (quench number 45 - 50 ). The $45^{th}$ (first 1.9K quench of the second test cycle) was at 9850A, which is about 30% below the short sample limit of the cable. Finally, 2 additional quenches were taken at 4.5K. In these studies the magnet was ramped to quench at 20A/sec.

## 2.2 Quench locations

Voltage taps that instrumented HGQS02 allowed for localization of most quenches. The locations of each spontaneous quench are summarized in Table 2.3.

Most of the spontaneous quenches occurred in the end regions and about 50% of them were at a particular location of the same coil.

Table 2.1: Instrumentation settings - spontaneous quenches

| | | |
|---|---|---|
| Dump Resistor | Resistance | $60 m\Omega$ |
| | Time Delay | $25 msec$ |
| Power Supply | Time Constant | $0.5 sec$ |
| HFU | Capacitance | $14.4 mF$ |
| | Time Delay | $0 - 20 msec$ |
| | Voltage | $300V@4.3K$ |
| | | $350V@1.9K$ |
| Data Logger | Sampling frequency | $7.4 kHz$ |
| | Pre-quench window | 50% |
| Current read back | Hollec | |

Table 2.2: QDC settings

| AQDC name | Threshold settings | Threshold values |
|---|---|---|
| Whole coil | 1.0 | 10 V |
| Whole coil - Idot | 0.09 | 0.9 V |
| Bucked Half coils | 0.06 | 0.24 V |
| SC Leads | 0.72 | 0.03 V |
| Cu Leads | 0.74 | 0.03 V |
| Ground | 1.26 | 0.1 V |

Table 2.3: Quench history. Test cycle I

| Quench num | T [K] | dI/dt [A/s] | $I_q$ [A] | Quench location |
|---|---|---|---|---|
| 1 | 4.5 | 20 | 7365 | Q2O15a_Q2O16b Le.end - 17% from 16b |
| 2 | 4.5 | 20 | 8654 | Q4O15a_Q4O16b Le.end - 42% from 15a |
| 3 | 4.5 | 20 | 8722 | Q2O15c_Q2O15d Re.end - 20% from 15d |
| 4 | 4.5 | 20 | 8757 | Q4I11c_Q4I11d Re.end - 46% from 11d |
| 5 | 4.5 | 20 | 8897 | Q4I11a_Q4I10b Le.end - 46% from 10b |
| 6 | 4.5 | 20 | 8985 | Q4I11c_Q4I11d Re.end - 46% from 11d |
| 7 | 4.5 | 20 | 9203 | Q3IOrs_Q3O16a Ramp Splice |
| 8 | 4.5 | 300 | 8250 | Q1IOrs_Q1I14b Le.end next to Vtap 14b |
| 9 | 1.9 | 20 | 9191 | Q4I11c_Q4I11d Re.end - 41% from 11d |
| 10 | 1.9 | 20 | 9401 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 11 | 1.9 | 20 | 9614 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 12 | 1.9 | 20 | 9797 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 13 | 1.9 | 20 | 9999 | Q4I11c_Q4I11d Re.end - 48% from 11d |
| 14 | 1.9 | 20 | 10147 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 15 | 1.9 | 20 | 10336 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 16 | 1.9 | 20 | 10523 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 17 | 1.9 | 20 | 10715 | Q4I11c_Q4I11d Re.end - 42% from 11d |
| 18 | 1.9 | 20 | 10849 | Q4I11a_Q4I10b Le.end - 22% from 11a |
| 19 | 1.9 | 20 | 10852 | Q4I11c_Q4I11d Re.end - 41% from 11d |
| 20 | 1.9 | 20 | 11058 | Q4I11c_Q4I11d Re.end - 41% from 11d |
| 21 | 1.9 | 20 | 11201 | Q4I11c_Q4I11d Re.end - 39% from 11d |
| 22 | 1.9 | 20 | 11317 | Q2I14a_Q2I13b Le.end - 45% from 13b |
| 23 | 1.9 | 20 | 11313 | Q4I11c_Q4I11d Re.end - 41% from 11d |
| 24 | 1.9 | 20 | 11364 | Q2O15c_Q2O15d Re.end - close to Vtap 15d |
| 25 | 1.9 | 20 | 11390 | Q2O14b_Q2O14d St.sec. - 49% from 14b |
| 26 | 1.9 | 20 | 11379 | Q1I13b_Q1I14c (broken voltage tap) |
| 27 | 1.9 | 20 | 11409 | Q4I11c_Q4I11d Re.end - 46% from 11d |
| 28 | 1.9 | 20 | 11398 | Q3I10b_Q3I11a Le.end - 45% from 13b |
| 29 | 1.9 | 20 | 11462 | Q2I14b_Q2I14d St.sec. - middle |
| 30 | 1.9 | 20 | 11492 | Q4I11a_Q4I11b Le.end - 49% from 10b |
| 31 | 1.9 | 20 | 11521 | Q4I11c_Q4I11d Re.end - 33% from 11d |
| 32 | 1.9 | 160 | 11335 | Q2I10b_Q2IL multiple turn |
| 33 | 1.9 | 300 | 11454 | Q3IOrs_Q3I14b Le.end next to Vtap 14b |
| 34 | 1.9 | 100 | 10665 | |
| 35 | 1.9 | 20 | 11471 | Q2O15c_Q2O15d Re.end |
| 36 | 1.9 | 20 | 11492 | Q4I14c_Q4I13b next to Vtap 13b |
| 37 | 1.9 | 20 | 11486 | q4I11c_Q4I11d Re.end |

Table 2.4: Quench history. Test cycle II

| Quench num | T [K] | dI/dt [A/s] | $I_q$ [A] | Quench location |
|---|---|---|---|---|
| 38 | 4.5 | 20 | 9386 | Q2O15c_Q2O15d Re.end |
| 39 | 4.5 | 20 | 9366 | Q1I13b_Q1I14b |
| 40 | 4.5 | 20 | 9525 | Q1I14a_Q1I13b close to 13b |
| 41 | 4.5 | 20 | 9584 | Q4I11c_Q4I11d Re.end |
| 42 | 4.5 | 20 | 9781 | Q2I13b_Q2I12b close to 13b |
| 43 | 4.5 | 300 | 8405 | Q1IOrs_Q1I14b Le.end |
| 44 | 4.5 | 150 | 9787 | |
| 45 | 1.9 | 20 | 9850 | Q4I11c_Q4I11d Re.end |
| 46 | 1.9 | 20 | 10094 | Q4I11c_Q4I11d Re.end |
| 47 | 1.9 | 20 | 10275 | Q4I11c_Q4I11d Re.end |
| 48 | 1.9 | 20 | 10453 | Q4I11c_Q4I11d Re.end |
| 49 | 1.9 | 20 | 10578 | Q4I11c_Q4I11d Re.end |
| 50 | 1.9 | 20 | 10776 | Q4I11c_Q4I11d Re.end |
| 51 | 4.5 | 20 | 10714 | Q2I11a_Q4I11c St.sec. |
| 52 | 4.5 | 20 | 10795 | Q3O16b_Q3O16d St.sec. |

Table 2.5: Quench files; test cycle I

| Quench num | File name |
|---|---|
| 1 | hgqs02.Quench.980528114003.133 |
| 2 | hgqs02.Quench.980528123540.838 |
| 3 | hgqs02.Quench.980528133352.998 |
| 4 | hgqs02.Quench.980528142421.515 |
| 5 | hgqs02.Quench.980528151609.780 |
| 6 | hgqs02.Quench.980528154735.498 |
| 7 | hgqs02.Quench.980528163916.659 |
| 8 | hgqs02.Quench.980528171531.569 |
| 9 | hgqs02.Quench.980529140628.419 |
| 10 | hgqs02.Quench.980529150609.319 |
| 11 | hgqs02.Quench.980529155256.149 |
| 12 | hgqs02.Quench.980529170212.996 |
| 13 | hgqs02.Quench.980529173539.281 |
| 14 | hgqs02.Quench.980529180919.184 |
| 15 | hgqs02.Quench.980529184526.454 |
| 16 | hgqs02.Quench.980529192047.525 |
| 17 | hgqs02.Quench.980530100606.144 |
| 18 | hgqs02.Quench.980530110259.031 |
| 19 | hgqs02.Quench.980530114418.235 |
| 20 | hgqs02.Quench.980530122228.717 |
| 21 | hgqs02.Quench.980530132613.729 |
| 22 | hgqs02.Quench.980530140341.894 |
| 23 | hgqs02.Quench.980530144532.352 |
| 24 | hgqs02.Quench.980530153158.702 |
| 25 | hgqs02.Quench.980530161621.839 |
| 26 | hgqs02.Quench.980530172249.722 |
| 27 | hgqs02.Quench.980530181502.919 |
| 28 | hgqs02.Quench.980603163236.207 |
| 29 | hgqs02.Quench.980603173117.463 |
| 30 | hgqs02.Quench.980603183428.824 |
| 31 | hgqs02.Quench.980603201211.192 |
| 32 | hgqs02.Quench.980603210827.618 |
| 33 | hgqs02.Quench.980604150020.659 |
| 34 | hgqs02.Quench.980612103544.181 |
| 35 | hgqs02.Quench.980612143000.153 |
| 36 | hgqs02.Quench.980612150954.316 |
| 37 | hgqs02.Quench.980612154453.623 |

Table 2.6: Quench files, test cycle II

| Quench num | File name |
|---|---|
| 38 | hgqs02.Quench.980629174535.871 |
| 39 | hgqs02.Quench.980629183228.192 |
| 40 | hgqs02.Quench.980629195734.266 |
| 41 | hgqs02.Quench.980629203558.294 |
| 42 | hgqs02.Quench.980629211359.548 |
| 43 | hgqs02.Quench.980629215025.493 |
| 44 | hgqs02.Quench.980629222240.990 |
| 45 | hgqs02.Quench.980630205029.376 |
| 46 | hgqs02.Quench.980630212956.111 |
| 47 | hgqs02.Quench.980630221532.799 |
| 48 | hgqs02.Quench.980702105029.592 |
| 49 | hgqs02.Quench.980702113229.480 |
| 50 | hgqs02.Quench.980702130030.589 |
| 51 | hgqs02.Quench.980706105939.309 |
| 52 | hgqs02.Quench.980706122334.858 |

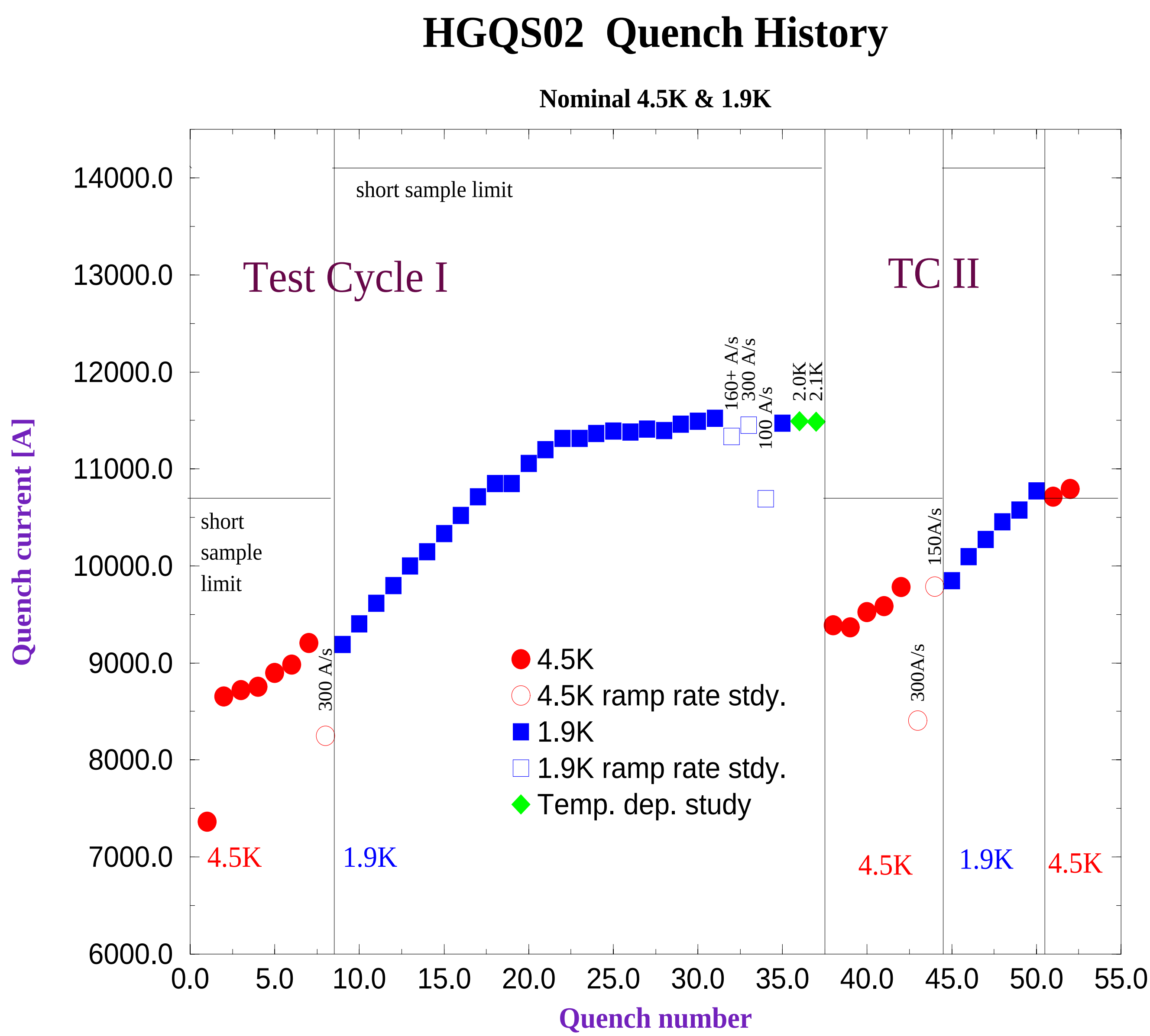


Figure 2.1: Quench history (qhist.eps)

# Chapter 3

# Quench protection heater study

This chapter presents the results of the quench protection heater studies.

## 3.1 Quench protection heaters

The magnet was instrumented with outer and interlayer strip heaters. Spot heaters were also installed in inner and outer coils. The details of these heaters are described elsewhere. The instrumentation settings are summarized in table 3.1.

## 3.2 Strip Heater induced quenches

In the strip heater studies, the time delay, $t_{fn}$ (the time from protection heater current initiation to the presence of a detectable quench voltage in the outer coils), was measured as a function of various normalized current values ($I/I_c$). The result for both the outer and for the interlayer heaters are shown in figure 3.1 and in table 3.4. One can conclude that the interlayer heater is as efficient as the outer heater.

## 3.3 Spot Heater induced quenches

The main purpose of this study was to measure the quench integral vs. the applied current and the quench propagation velocity during spot heater induced quenches. For most of the quenches the dump was not used to extract the energy. It was delayed for 1 sec. Both interlayer and outer heater were used to protect the magnet. The applied voltage was 400V. No heater delay was applied.

First we determined the minimum voltage to initiate a quench with a spot heater. We increased the voltage in 2 V increments until a quench was observed. 11V was sufficient to initiate a quench.

Then we set the Spot heater firing unit voltage to 25 V and this value was used for all spot heater studies.

The quench integral in MIITs ( $10^6 A^2 s$) is plotted in Fig. 3.2 as a function of the applied current for quenches induced with the inner spot heaters and protected either with the outer (solid symbols) or interlayer (open symbols) heaters. There are four family of curves; the upper set (circles) represents the quench integral with a starting time at the onset of the spot heater induced resistive voltage (segment label: Q1I14b-Q1IORS), the set labeled with squares is the quench integral with a starting time corresponding to the 300 mV quench detection, the lower set (diamond) represents the quench integral from the onset of voltage growth in the outer coil due to the strip heaters and the set labeled with triangles represents the quench integral with a starting time at the onset of an outer cable segment (across the spilce: Q1O16a-Q1IORS) resistive voltage.

Temperature of outer and inner cable segments vs. the quench integral in MIITs ( $10^6 A^2 s$) is plotted in Fig. 3.3.

Table 3.1: Instrumentation settings - heater induced quenches

| | | |
|---|---|---|
| Dump Resistor | Resistance | $60m\Omega$ |
| | Time Delay | $25msec$ |
| Power Supply | Time Constant | $0.5sec$ |
| HFU | Capacitance | $14.4mF$ |
| | Voltage | $90-400V@1.9K$ |
| Data Logger | Sampling frequency | $7.4kHz$ |
| | Pre-quench window | 50% |
| Current read back | Hollec | |

Table 3.2: Heater induced quench files

| Quench num | Current [Amps] | temp [K] | Spot heater name & [volt] | Strip heater name & [volt] | File name |
|---|---|---|---|---|---|
| 1 | 3000 | 1.9 | innerQ1 11 | outer 400 | hgqs02.Quench.980609143719.965 |
| 2 | 3000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980609153703.725 |
| 3 | 5000 | 1.9 | innerQ1 11 | outer 400 | hgqs02.Quench.980609171240.848 |
| 4 | 6000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980609183250.832 |
| 5 | 7000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980610140143.885 |
| 6 | 8000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980610154634.424 |
| 7 | 8000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980610161545.179 |
| 8 | 9000 | 1.9 | innerQ1 25 | outer 400 | hgqs02.Quench.980610180118.557 |
| 9 | 3000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980610202132.923 |
| 10 | 3000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980610203948.103 |
| 11 | 5000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980610211208.485 |
| 12 | 7000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980610214515.896 |
| 13 | 9000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980610223939.725 |
| 14 | 10000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980611112039.791 |
| 15 | 11000 | 1.9 | innerQ1 25 | inter 400 | hgqs02.Quench.980611142225.235 |
| 16 | 3000 | 1.9 | outerQ4 25 | inter 400 | hgqs02.Quench.980612112506.919 |
| 17 | 3000 | 1.9 | outerQ4 25 | inter 400 | hgqs02.Quench.980612121717.576 |
| 18 | 3000 | 1.9 | outerQ4 25 | inter 400 | hgqs02.Quench.980612125055.205 |
| 19 | 5000 | 1.9 | outerQ4 25 | inter 400 | hgqs02.Quench.980612130451.821 |
| 20 | 10500 | 1.9 | | inter 400 | hgqs02.Quench.980702142930.210 |
| 21 | 10500 | 1.9 | | outer 400 | hgqs02.Quench.980702164556.406 |
| 22 | 2800 | 1.9 | | outer 400 | hgqs02.Quench.980702171616.334 |
| 23 | 5600 | 1.9 | | outer 400 | hgqs02.Quench.980702173434.460 |
| 24 | 2800 | 1.9 | | inter 400 | hgqs02.Quench.980702175744.381 |
| 25 | 5600 | 1.9 | | inter 400 | hgqs02.Quench.980702180558.026 |
| 26 | 9500 | 1.9 | | inter 400 | hgqs02.Quench.980702181522.947 |

Table 3.3: Heater induced quench measured quantities. (QI = Quench Integral; t = time to start measuring QI; R = resistance, in = inner cable segment, out = outer cable segment; T = temperature)

| Quench num | $t_{fn}$ [sec] | QI [MIITs] $t = 0$ | QI [MITTs] $t = t_{fn}$ | R in [$\mu\Omega$] | R out [$\mu\Omega$] | QI in [MIITs] | QI out [MIITs] | T in [K] | T out [K] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.098 | 5.00729 | 4.1648 | | | | | | |
| 2 | 0.098 | 5.00174 | 4.1597 | 5.6 | 5.7 | 12.4 | 6.95 | 40.3 | 34 |
| 3 | 0.050 | 9.88682 | 8.67065 | 22.9 | 20.2 | 15.25 | 11.4 | 68.4 | 59.5 |
| 4 | 0.043 | 11.6362 | 10.1258 | 38.0 | 33.6 | 16.8 | 12.7 | 86.7 | 75.7 |
| 5 | 0.038 | 12.9663 | 11.1477 | 53.1 | 49.4 | 17.7 | 13.8 | 103.4 | 92.1 |
| 6 | 0.033 | 4.36079 | 2.33012 | | | | | | |
| 7 | 0.033 | 13.9659 | 11.901 | 66.6 | 65.3 | 18.4 | 14.6 | 117.5 | 107.4 |
| 8 | 0.029 | 14.7982 | 12.4924 | 80.0 | 80.9 | 18.8 | 15.2 | 131.0 | 121.7 |
| 9 | 0.060 | 0.626151 | 0.0851369 | | | | | | |
| 10 | 0.060 | 4.87564 | 4.35242 | 5.7 | 5.6 | 11.8 | 6.8 | 40.5 | 33.9 |
| 11 | 0.057 | 9.53642 | 8.15018 | 22.8 | 19.2 | 15.2 | 11.1 | 68.2 | 58.5 |
| 12 | 0.045 | 12.4216 | 10.2692 | 48.9 | 44.2 | 17.1 | 13.2 | 99.0 | 86.7 |
| 13 | 0.032 | 14.1581 | 11.6195 | 74.6 | 73.5 | 18.1 | 14.6 | 125.5 | 115.0 |
| 14 | 0.026 | 14.8108 | 12.2632 | 84.0 | 85.2 | 18.3 | 15.0 | 135.0 | 125.7 |
| 15 | 0.023 | 15.4001 | 12.6626 | 115.6 | 122.5 | 17.0 | 13.9 | 165.9 | 158.5 |
| 16 | 0.060 | 0.637891 | 0.199626 | | | | | | |
| 17 | 0.060 | 0.638027 | 0.199671 | | | | | | |
| 18 | 0.060 | 4.8404 | 4.31802 | | | | | | |
| 19 | 0.057 | 9.50145 | 8.11676 | | | | | | |

Table 3.4: Strip heater induced quench measured quantities.

| Quench num | $t_{fn}[sec]$ ADC signal | $t_{fn}$ [sec] $8^{th}$ coil signal ($33\mu\Omega$) | $t_{fn}$ [sec] $8^{th}$ coil signal ($66\mu\Omega$) |
|---|---|---|---|
| 20 | 0.024 | .041 | .045 |
| 21 | 0.022 | .034 | .038 |
| 22 | 0.108 | .157 | .168 |
| 23 | 0.045 | .087 | .127 |
| 24 | 0.060 | .145 | .181 |
| 25 | 0.056 | .095 | .145 |
| 26 | 0.029 | .044 | .049 |

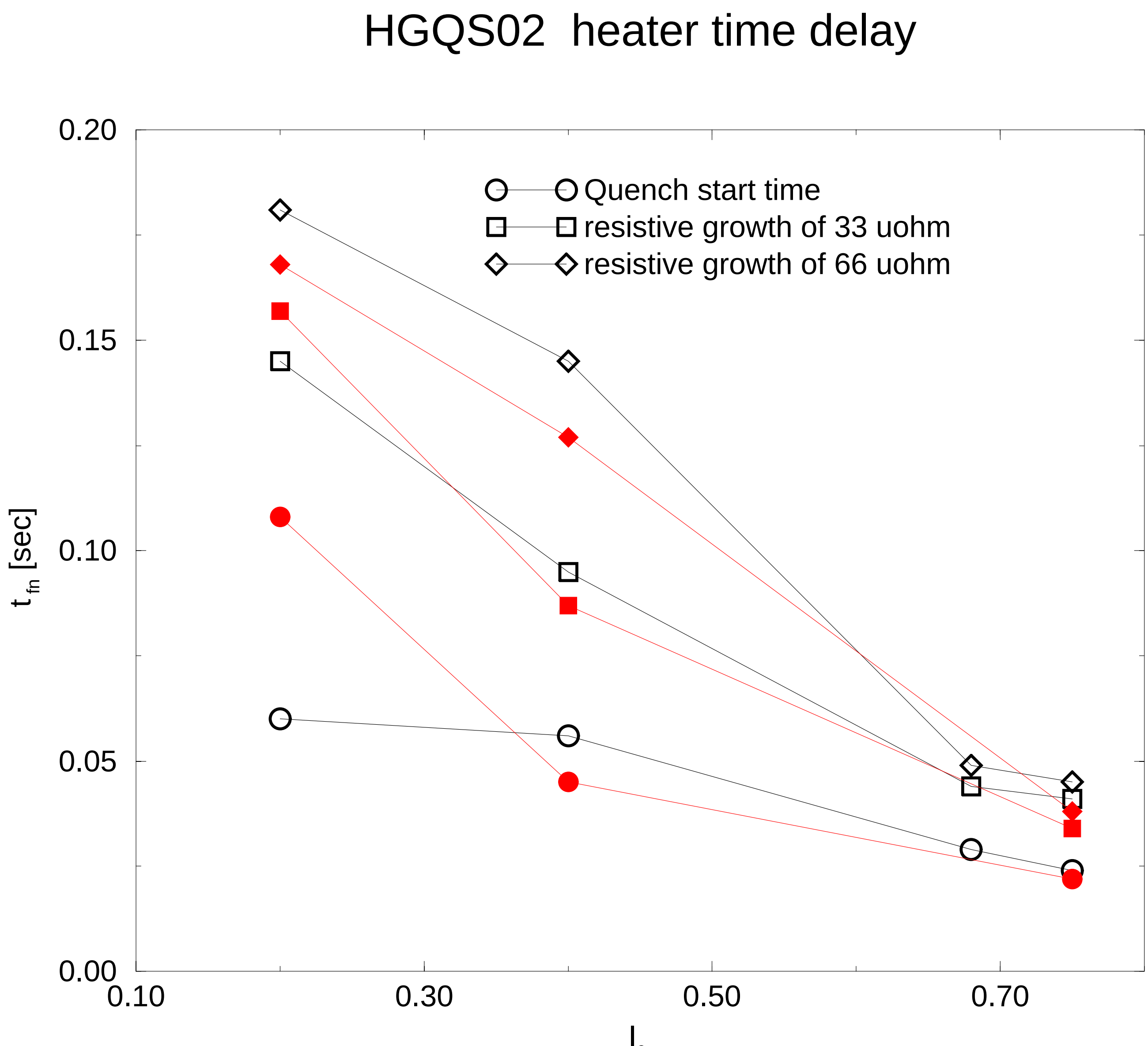


Figure 3.1: Heater induced quenches. $t_{fn}$ is plotted as a function of the normalized current. The magnet is protected with inter layer (solid symbol) or outer layer heaters (open symbol) The circle represents the $t_{fn}$ values when AQD signal is used to find the quech initiation time, the square and diamond symbola represent the $t_{fn}$ values when $8^{th}$ coil signal is used to find the quench initiation time. For the $8^{th}$ coil quench initiation times, a fixed resistance of 33 and 66$\mu\Omega$ was used as a threshold to indicate the start of a quench.

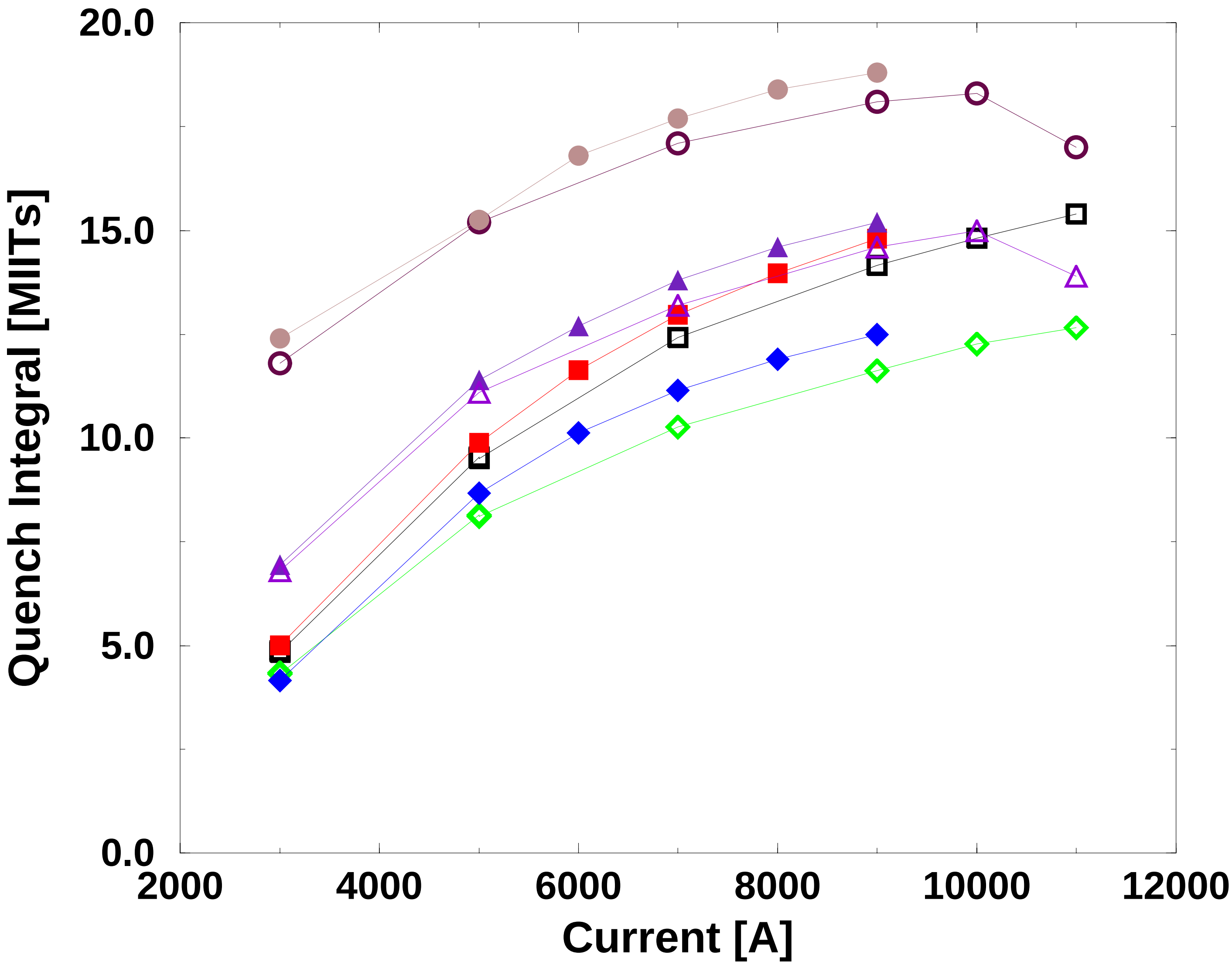


Figure 3.2: Quench integral vs. magnet current for spot heater induced quenches. The magnet is protected with inter layer (open symbol) or outer layer heaters (solid symbol), circle symbol: quench integral from time of spot heater quench initiation, triangle symbol: quench integral from time the outer cable detected the quench, square symbol: quench integral from quench detection time, diamonds: quench integral from strip heater voltage onset.

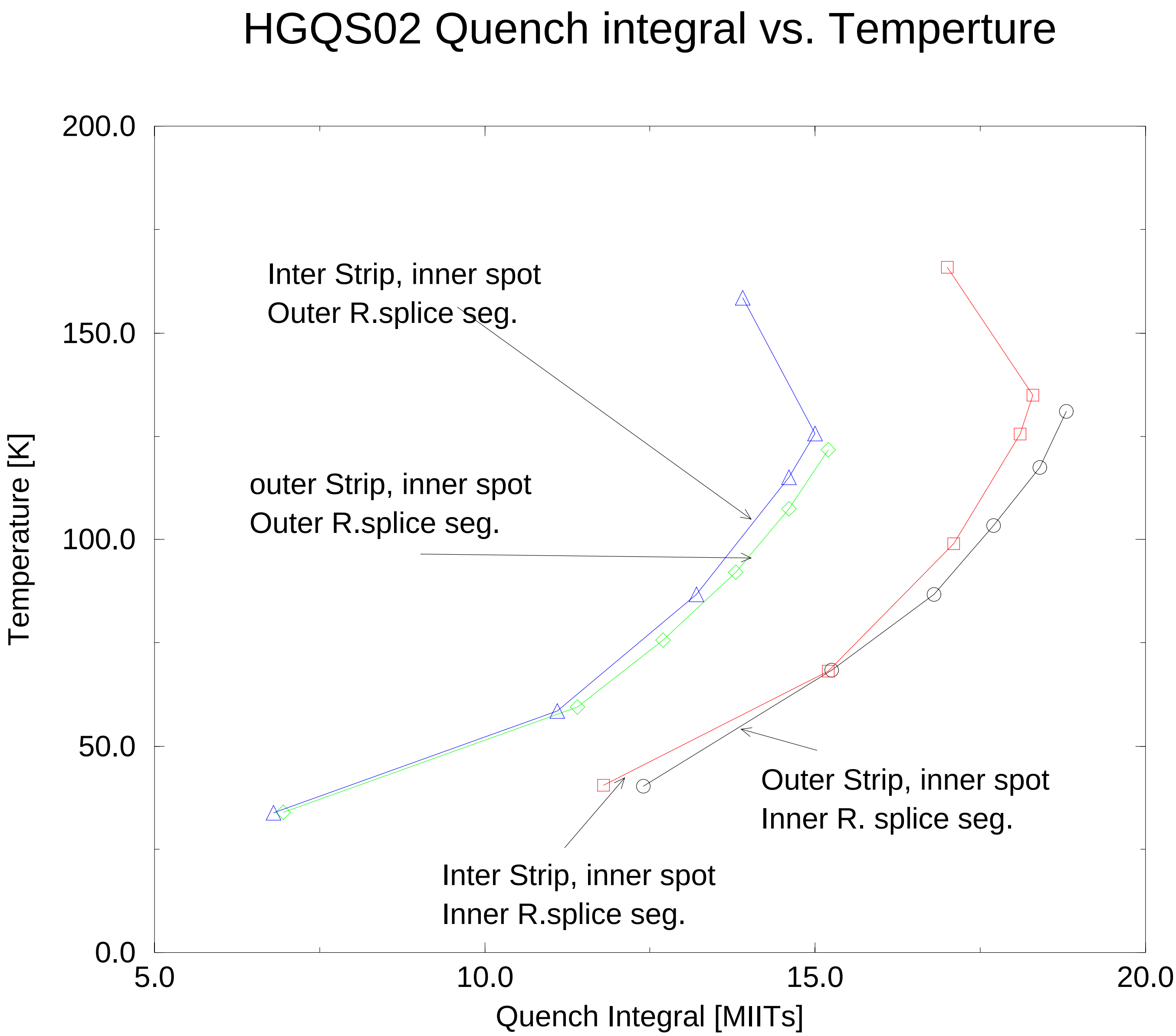


Figure 3.3: Temperature of outer and inner cable segments vs. the quench integral in MIITs ( $10^6 A^2 s$) is plotted

# Chapter 4

# Strain Gauge Results

## 4.1 Instrumentation Details

Magnet HGQs02 is instrumented with an assortment of strain gauges to measure azimuthal coil stresses and coil end forces. These strain gauges are calibrated at room temperature and at liquid Helium temperature, are read out during various phases of the magnet construction process, and during cryogenic testing.

A total of eight beam-type strain gauges are used to measure azimuthal stresses in the straight section of the coils, four mounted at the inner coils, four mounted at the outer coils. Each active strain gauge has a compensating gauge associated with it, whose purpose is to provide an independent measure of the apparent strains induced in the active gauges due to thermal contraction and magneto-resistance effects.

Four capacitance-type strain gauges were also installed in the straight section of the inner coils to measure azimuthal stress. Each of these gauges were installed in such a way that they were in the same collared coil cavity as one of the inner coil beam gauges. Additionally, four capacitance gauges were mounted on the end saddles of the coils to monitor pre-stress during assembly and cryogenic operation.

A total of eight bullet-type gauges are used to measure the end forces associated with each inner/outer coil pair. Four bullet gauges are mounted at the return-end of the magnet, while four are mounted at the lead end. Each bullet gauge consists of two strain gauges whose readings are subsequently averaged to eliminate strains resulting from bending of the transducer structure. The resultant strain is then used to compute the force on the bullet. Two compensating gauges are placed at each end of the magnet, whose readings are averaged in order to provide apparent strain data used in eliminating apparent strains from the active gauges.

Table 4.1 I gives the list of coil azimuthal strain gauges, names, and locations for magnet HGQS02, while Table 4.2 lists the same information for the bullet gauges, and Table 4.3 lists this information for capacitance strain gauges.

Table 4.1: Beam Gauges

| Gauge ID | Type | Coil | Function | Quadrant | End | VMTF Name |
|---|---|---|---|---|---|---|
| LHCI003 | Beam | Inner | Active | Quad 2 | LE | BmAcQ2IL |
| LHCI004 | Beam | Inner | Active | Quad 4 | LE | BmAcQ4IL |
| LHCI005 | Beam | Inner | Active | Quad 2 | RE | BmAcQ2IR |
| LHCI006 | Beam | Inner | Active | Quad 4 | RE | BmAcQ4IR |
| LHCTC02 | Beam | Inner | Comp | Quad 2 | LE | BmCoQ2IL |
| LHCTC04 | Beam | Inner | Comp | Quad 4 | LE | BmCoQ4IL |
| LHCTC05 | Beam | Inner | Comp | Quad 2 | RE | BmCoQ2IR |
| LHCTC07 | Beam | Inner | Comp | Quad 4 | RE | BmCoQ4IR |
| LHCO005 | Beam | Outer | Active | Quad 1 | LE | BmAcQ1OL |
| LHCO004 | Beam | Outer | Active | Quad 3 | LE | BmAcQ3OL |
| LHCO007 | Beam | Outer | Active | Quad 1 | RE | BmAcQ1OR |
| LHCO008 | Beam | Outer | Active | Quad 3 | RE | BmAcQ3OR |
| LHCTC08 | Beam | Outer | Comp | Quad 1 | LE | BmCoQ1OL |
| LHCTC10 | Beam | Outer | Comp | Quad 3 | LE | BmCoQ3OL |
| LHCTC11 | Beam | Outer | Comp | Quad 1 | RE | BmCoQ1OR |
| LHCTC13 | Beam | Outer | Comp | Quad 3 | RE | BmCoQ3OR |

## 4.2 Measurement Schedule

Strain gauge readings are performed several times during the magnet construction and testing cycles. Azimuthal coil stresses, measured with beam-

Table 4.2: Bullet Gauges

| Production Gauge Nam | VMTF Gauge Nam | Gauge Type | Gauge Location | Remarks |
|---|---|---|---|---|
| BL09A/B | BuQ1R | Bullet, active | Quad 1, RE | |
| BL10A/B | BuQ4R | Bullet, active | Quad 4, RE | |
| BL11A/B | BuQ2R | Bullet, active | Quad 2, RE | |
| BL12A/B | BuQ3R | Bullet, active | Quad 3, RE | |
| BL13A/B | BuQ1L | Bullet, active | Quad 1, LE | |
| BL14A/B | BuQ2L | Bullet, active | Quad 2, LE | |
| BL15A/B | BuQ3L | Bullet, active | Quad 3, LE | |
| BL16A/B | BuQ4L | Bullet, active | Quad 4, LE | |
| BT26 | BuCoR_1 | Bullet, comp. | RE | Comp. for RE bullets |
| BT30 | BuCoR_2 | Bullet, comp. | RE | “ |
| BT28 | BuCoL_1 | Bullet, comp. | LE | Comp. for LE bullets |
| BT29 | BuCoL_2 | Bullet, comp. | LE | ” |

type and capacitance strain gauges, are measured during the collaring and yoking/skinning assembly procedures. After the end plates are installed onto the magnet cold mass, the bullet gauges are then installed and the end loading screws torqued to achieve the desired end loads, while the bullet gauges are monitored.

Once cold mass fabrication has been completed, the magnet is moved to the magnet test facility, and prepared for cryogenic testing. Before, during, and after cryogenic testing all strain gauges are monitored. In particular, strain gauge data is acquired while ramping the magnet before and during quench training at 4.5K and 1.9K. Finally, the strain gauges are read out once the cold mass has been warmed back up to room temperature, so that comparisons with pre-cold test data can be made.

## 4.3 Results

The azimuthal coil stresses as measured by beam gauges are summarized in Table 4.4, which shows the coil stresses (measured in psi) during various

Table 4.3: Capacitance Gauges

| Gauge ID | Coil | Function | Quadrant | End | VMTF Name |
|---|---|---|---|---|---|
| HQCGI16 | Inner | Active | Quad 1 | LE | CgAcQ1IL |
| HQCGI19 | Inner | Active | Quad 3 | LE | CgAcQ3IL |
| HQCGI30 | Inner | Active | Quad 1 | RE | CgAcQ1IR |
| HQCGI32 | Inner | Active | Quad 3 | RE | CgAcQ3IR |
| HQCGR34 | Saddle | Active | Quad 2-3 | LE | CgAcQ23SL |
| HQCGR35 | Saddle | Active | Quad 2-3 | RE | CgAcQ23SR |
| HQCGL36 | Saddle | Active | Quad 1-4 | RE | CgAcQ14SR |
| HQCGL37 | Saddle | Active | Quad 1-4 | LE | CgAcQ14SL |

fabrication and operational conditions. End loads for the coils (in lbs) are likewise given in Table 4.5. Figure 4.1 shows the azimuthal coil stress history of the cold mass during fabrication, through yoking/skinning in ICB, and at various cryogenic conditions. Figure 4.2 shows the same data for the coil end loads.

In Figures 4.3, 4.4 and 4.5 we show the results of strain gauge, bullet gauge, and skin gauge measurements as a function of $I^2$ for a quench run to 11201A at 1.9K. Note that the azimuthal coil stresses remain non-zero for all values of excitation current. There is no evidence of coil unloading at even the highest current level reached. Furthermore, extrapolation indicates that the lowest pre-loaded coil would only reach zero azimuthal stress at currents above 13.4 kA, somewhat below the conductor limit at 1.9K, but well above the designed operating current.

The plot of end loading (Fig. 4.4) indicates that though the initial end loads at 300K were between 1600 and 3000 lbs/quadrant, the coils were essentially unloaded at cryogenic temperatures. In fact, only one coil (Quad 4, Lead End) appeared to be in contact with the end plate at liquid helium temperatures with no current in the magnet. The other quadrants made contact with the end pate only after significant current was applied (see Table 4.5); indeed at 4.5K, and hence, lower maximum currents, some coils failed to contact the end plate at all before a quench occurred (e.g., quadrants 2 & 3, both ends). Furthermore, it was noted that the effects of training on the longitudinal position of the coils were not reversible - the onset of contact

Table 4.4: HGQS02 Coil Stresses

| Gauge | Condition<br>300K, Yoked | 300K, VMTF | 4.5K, I=0 | 4.5K, I=9203A | 1.9K, I=0 | 1.9K, I=11409A |
|---|---|---|---|---|---|---|
| Q2IL | 2902 | 3350 | 7644 | 4424 | 7879 | 2227 |
| Q2IR | 13869 | 13740 | 13580 | 9415 | 13754 | 7145 |
| Q4IL | 7969 | 8270 | 9893 | 6657 | 10042 | 4659 |
| Q4IR | 9763 | 10820 | 11605 | 8080 | 12309 | 6055 |
| Average | 8626 | 9045 | 10681 | 7144 | 10996 | 5022 |
| Q1OL | 9549 | BAD | BAD | BAD | BAD | BAD |
| Q1OR | 15791 | 16141 | 16680 | 14808 | 17600 | 14194 |
| Q3OL | 10428 | 11040 | 9527 | 7861 | 10894 | 7687 |
| Q3OR | 13044 | 13600 | 10370 | 9109 | 10897 | 8695 |
| Average | 12203 | 13594 | 12192 | 10593 | 13130 | 10192 |

with the end pates occurred at lower currents for subsequent quenches. Between test cycles, the end loading screws at the return end were completely loosened to ensure that the coils would not contact the return end plates at any operating current, in order to determine the effects of longitudinal restraint on training. No effect was observed.

The skin gauges indicated marginal levels of skin stress as a function of $I^2$ (Fig. 4.5) not inconsistent with that expected if the total end loads as measured by the bullet gauges were to be transferred to the shell at the end plate. The gauge mounted closest to the return end measured a skin strain that was somewhat higher than indicated by end loading considerations, but not by a significant amount.

The plots shown in Figures 4.3-4.5 are typical of all of the quench runs at 4.5K and 1.9K. No anomalous behavior was observed during cryogenic testing. Additional data/plots can be found on the Web at $http://mdtf20.fnal.gov/\sim ozelis/HGQS02$ . The dynamic mechanical behavior of magnet HGQS02 is summarized in Table 4.8. This behavior is very similar to that of magnet HGQS01, yet the quench locations and behavior were significantly different. It would appear that the mechanical behavior described by these data is de-coupled from the mechanism that is

Table 4.5: End loads (in lb)

| Bullet | Condition 300K, Yoked | 300K, VMTF | 4.5K, I=0A | 4.5K, I=9203A | 1.9K, I=0A | 1.9K, I=11409A | 1.9K Load starts (A) | 4.5K Load starts (A) |
|---|---|---|---|---|---|---|---|---|
| Q1R | 2850 | 2250 | -890 | -475 | -198 | 920 | 6320 | 7420 |
| Q2R | 3288 | 2700 | -1033 | -866 | -408 | 467 | 8950 | > 9200 |
| Q3R | 2848 | 2300 | -1133 | -931 | -117 | 521 | 8775 | > 9200 |
| Q4R | 2572 | 3000 | -940 | -734 | | | | 8660 |
| Total | 11558 | 10250 | -3996 | -3006 | -723 | 1908 | | |
| Average | 2890 | 2563 | -999 | -752 | -181 | 477 | | |
| | | | | | | | | |
| Q1L | 1914 | 1920 | -1005 | -294 | -344 | 1190 | 5000 | 6600 |
| Q2L | 2050 | 1600 | -1068 | -903 | -240 | 797 | 8000 | > 9200 |
| Q3L | 1920 | 1600 | -1084 | -841 | -247 | 886 | 8180 | > 9200 |
| Q4L | 1975 | 1650 | -1029 | 30 | -154 | 1822 | 0 | 3500 |
| Total | 7859 | 6770 | -4186 | -2008 | -985 | 4695 | | |
| Average | 1965 | 1693 | -1047 | -502 | -246 | 1174 | | |

responsible for the quenches/training in magnet HGQS02.

Table 4.6: Coil Stress Changes (-ve = loss)

| Gauge | Condition Yoked-VMTF (300K) | VMTF (300K-4.5K) | VMTF (300K-1.9K) | VMTF (4.5K-1.9K) | 4.5K 0 - 9203 A | 1.9K 0 -11409 A |
|---|---|---|---|---|---|---|
| Q2IL | 448 | 4294 | 4529 | 235 | -3220 | -5652 |
| Q2IR | -129 | -160 | 14 | 174 | -4165 | -6609 |
| Q4IL | 301 | 1623 | 1772 | 149 | -3236 | -5383 |
| Q4IR | 1057 | 785 | 1489 | 704 | -3525 | -6254 |
| Average | 419 | 1636 | 1951 | 316 | -3537 | -5975 |
| | | | | | -4.17E-05 | -4.59E-05 |
| | | | | | $(psi/A^2)$ | $(psi/A^2)$ |
| Q1OL | | | | | | |
| Q1OR | 350 | 539 | 1459 | 920 | -1872 | -3406 |
| Q3OL | 612 | -1513 | -146 | 1367 | -1666 | -3207 |
| Q3OR | 556 | -3230 | -2703 | 527 | -1261 | -2202 |
| Average | 506 | -1401 | -463 | 938 | -1600 | -2938 |
| | | | | | -1.89E-05 | -2.26E-05 |
| | | | | | $(psi/A^2)$ | $(psi/A^2)$ |

Table 4.7: End load changes (in lb)

| Bullet | Condition Yoked-VMTF (300K) | VMTF (300K-4.5K) | VMTF (300K-1.9K) | VMTF (4.5K-1.9K) | 4.5K 0 - 9203 A | 1.9K 0 -11409 A | $\Delta$ Force/ $kA^2$ | $\Delta$ Force/ $kA^2$ |
|---|---|---|---|---|---|---|---|---|
| Q1R | -600 | -3140 | -2448 | 692 | 415 | 1118 | 1.24E-05 | |
| Q2R | -588 | -3733 | -3108 | 625 | 167 | 875 | 1.75E-05 | |
| Q3R | -548 | -3433 | -2417 | 1016 | 202 | 638 | 1.20E-05 | |
| Q4R | 428 | -3940 | | | 206 | | | |
| Total | -1308 | -14246 | -7973 | 2333 | 990 | 2631 | | |
| Average | -327 | -3562 | -2658 | 778 | 330 | 877 | 1.40E-05 | 1.60E-05 |
| Q1L | 6 | -2925 | -2264 | 661 | 711 | 1534 | 1.46E-05 | |
| Q2L | -450 | -2668 | -1840 | 828 | 165 | 1037 | 1.57E-05 | |
| Q3L | -320 | -2684 | -1847 | 837 | 243 | 1133 | 1.80E-05 | |
| Q4L | -325 | -2679 | -1804 | 875 | 1059 | 1976 | 1.52E-05 | |
| Total | -1089 | -10956 | -7755 | 3201 | 2178 | 5680 | | |
| Average | -272 | -2739 | -1939 | 800 | 545 | 1420 | 1.58E-05 | 1.70E-05 |

Figure 4.1: Summary of azmiuthal coil stress as measured by beam gauges.

Figure 4.2: Summary of coil end loads after fabrication and during cryogenic operation.

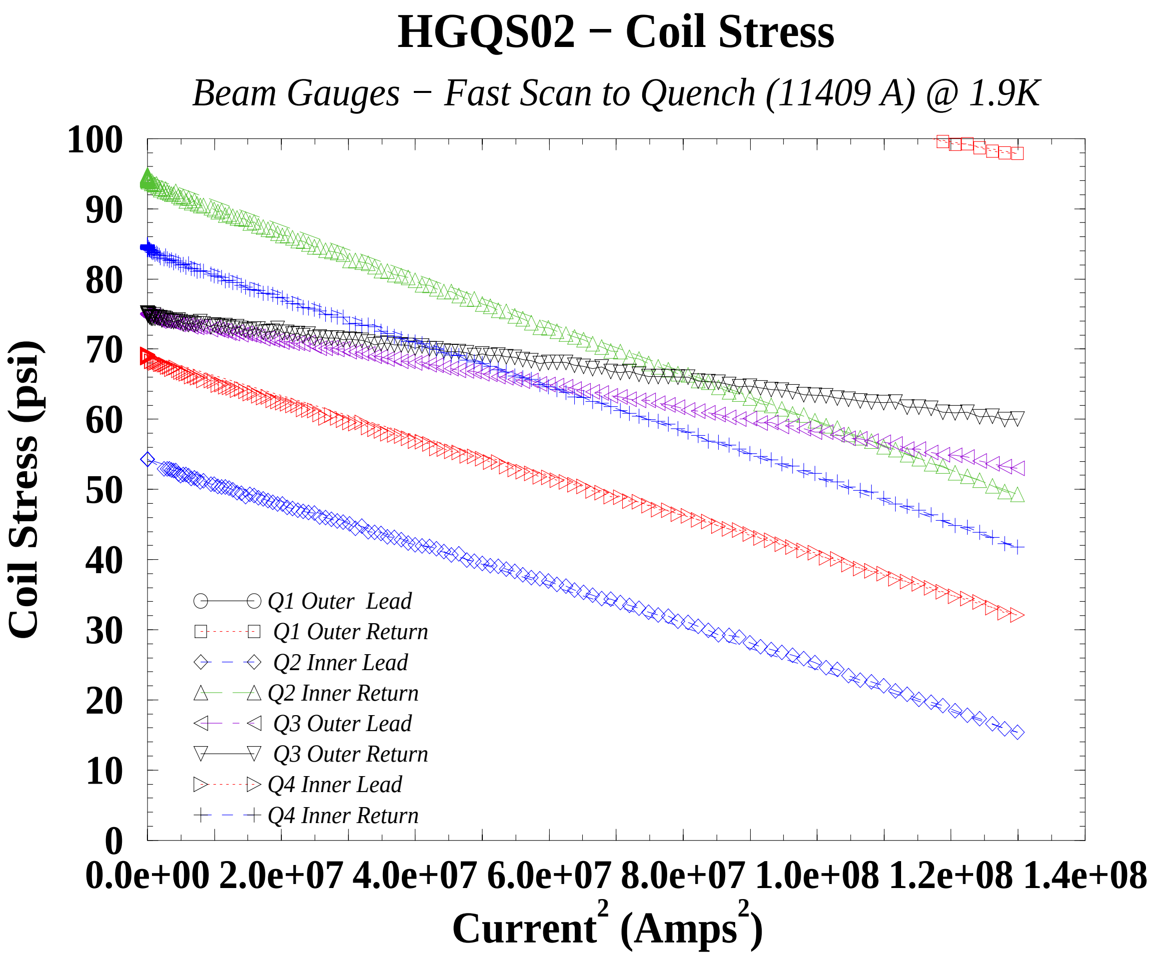


Figure 4.3: Azimuthal coil stress measured by beam gauges for a run to quench (11400A) at 1.9K.

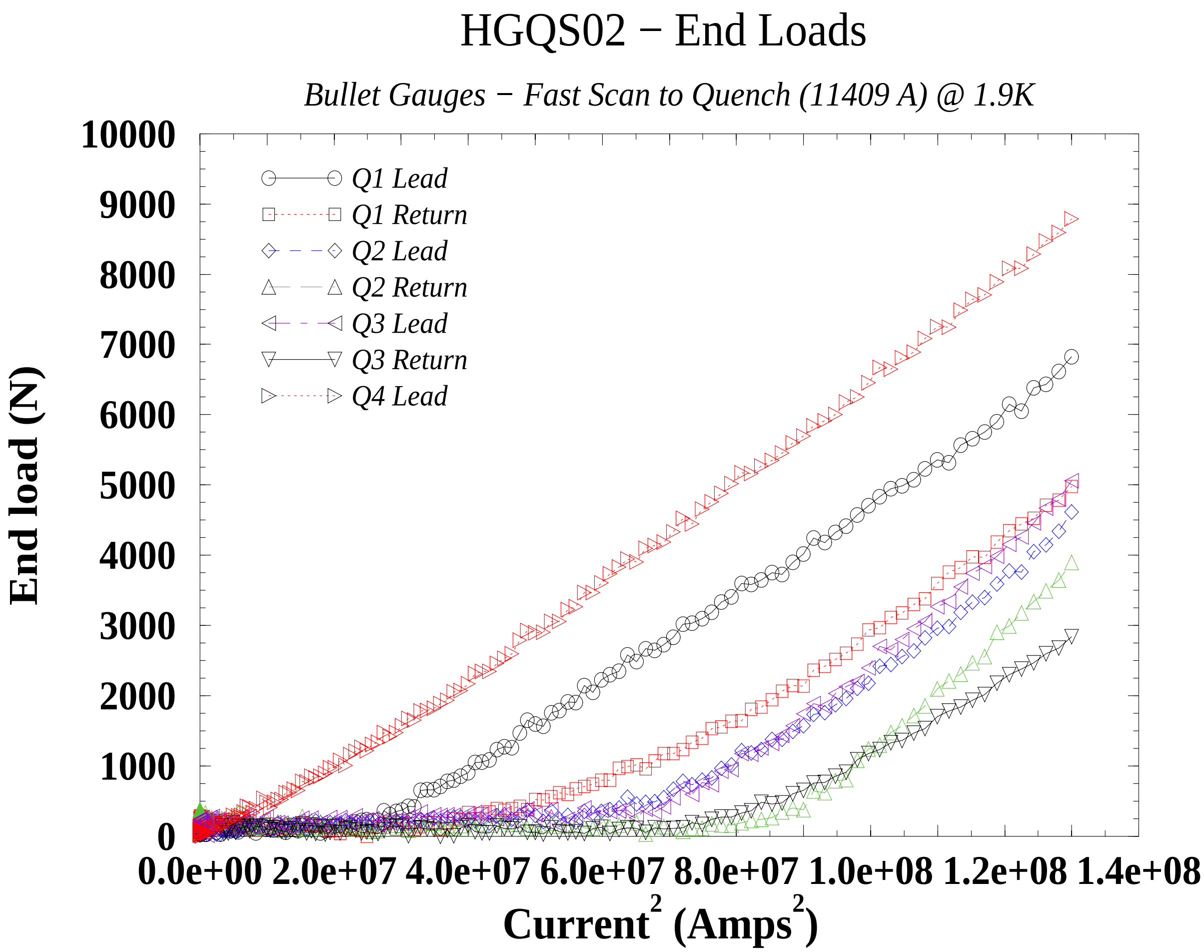


Figure 4.4: End loads as measured by bullet gauges for a run to quench (11400A) at 1.9K.

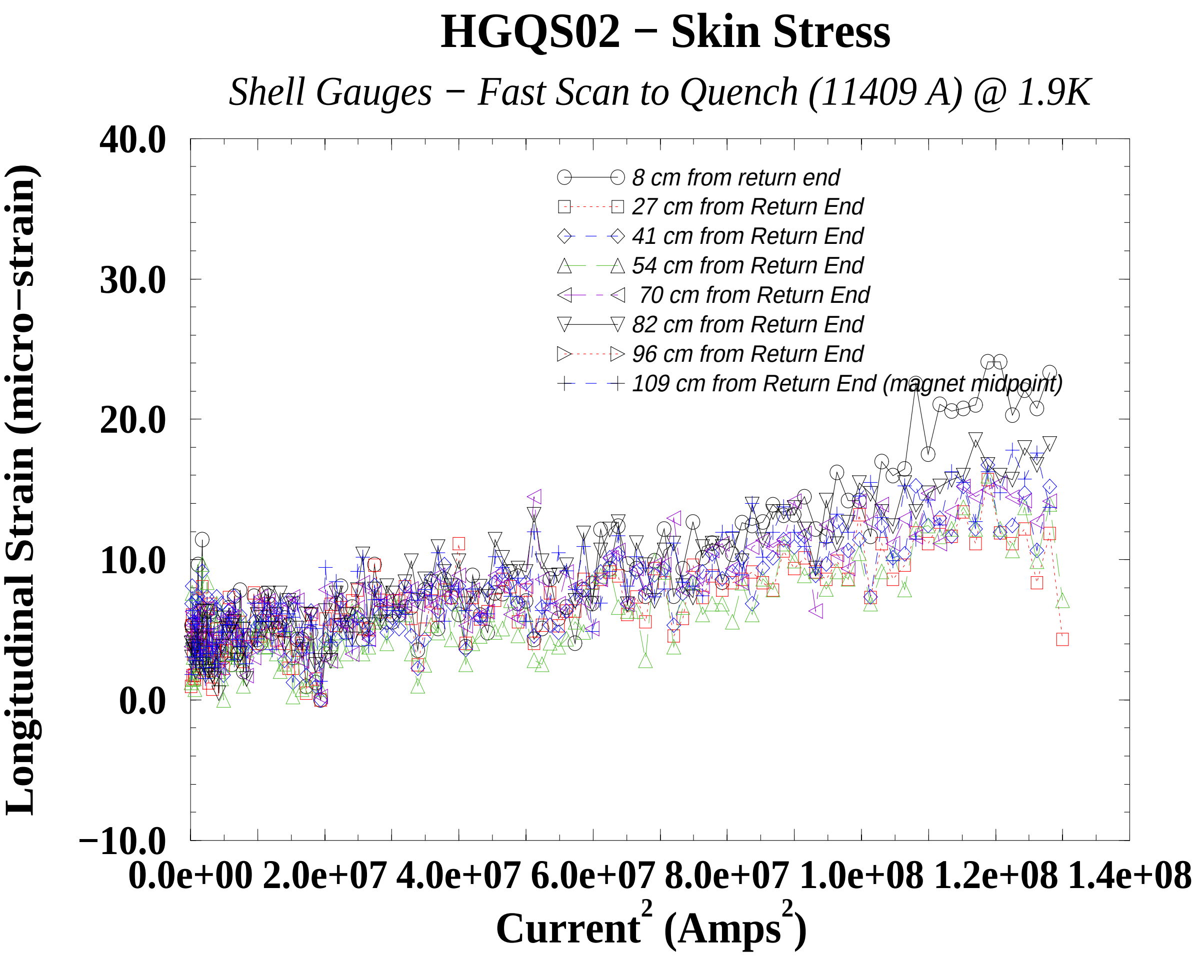


Figure 4.5: Longitudinal skin strain as measured by skin gauges for a run to quench (11400A) at 1.9K.

Table 4.8: Cryogenic Test Results

| | measured | predicted |
|---|---|---|
| Average Inner Coil Cool-Down Gain | $1600 - 1900psi$ ($11 - 13MPa$) | $600psi$ ($4MPa$) |
| Average Outer Coil Cool-Down Loss | $500 - 1400psi$ ($3 - 10MPa$) | $1450psi$ ($10MPa$) |
| Average Inner Coil Lorentz Loss | $4.2 - 4.6x10^{-5}psi/A^2$ ($2.9 - 3.2x10^{-7}MPa/A2$) | $4.4x10^{-5}psi/A^2$ ($3.0x10^{-7}MPa/A^2$) |
| Average Outer Coil Lorentz Loss | $1.9 - 2.3x10^{-5}psi/A^2$ ($1.3 - 1.6x10^{-7}MPa/A2$) | $2.9x10^{-5}psi/A^2$ ($2.0x10^{-7}MPa/A^2$) |
| Average Lead End Lorentz Loss | $1.7x10^{-5}lbsf/A^2$ ($7.6x10^{-5}N/A^2$) | $8.2x10^{-5}lbsf/A^2$ ($3.6x10^{-4}N/A^2$) |
| Average Return End Lorentz Loss | $1.6x10^{-5}lbsf/A^2$ ($7.1x10^{-5}N/A^2$) | $8.2x10^{-5}lbsf/A^2$ ($3.6x10^{-4}N/A^2$) |
| Skin Strains ( 1.9K, 11409 A) | RE08 : $18 \pm 4\mu\varepsilon$; RE70 : $9 \pm 4\mu\varepsilon$ | Based on total RE load expect $5 - 6\mu\varepsilon$ |
| | RE27 : $7 \pm 4\mu\varepsilon$; RE82 : $12 \pm 4\mu\varepsilon$ | |
| | RE41 : $10 \pm 4\mu\varepsilon$; RE96 : bad | |
| | RE54 : $7 \pm 4\mu\varepsilon$; RE109 : $11 \pm 4\mu\varepsilon$ | |

# Chapter 5

# RRR study

This chapter summarizes the residual resistance ratio (RRR) measurements. RRR is determined by measuring the coil resistance and temperature during magnet warm up.

Measurements of magnet resistance were made using a 4-wire technique at a current of 10A. Current was supplied by a Hewlett Packard Power Supply and voltages measured through the magnet voltage taps (see chapter 1). Both voltage and current measurements were made using HP3458A DMMs. For measurement of temperature we used Carbon-Glass sensors in the vicinity of the magnet. Two sensors were used, one of them closer to the top of the magnet and the other closer to the bottom. Note that these sensors were in fact reading the gas temperature and therefore one would expect the actual magnet temperature to be somewhat different.

Figures 5.1 and 5.2 compare the resistances of the eighth coils, measured while the magnet was gradually warming up, against the calculated room temperature resistances. For these plots, the average temperature of the top and bottom carbon glass sensors was used. We observed that the parameterization curve constrained by the resistance values measured at the lower temperatures does not agree well with the data measured at the higher temperatures. However, the magnet resistance around 10 K is not temperature dependent and therefore the error in RRR introduced by basing measurements on these points is not significant ($< 10\%$).

Note that the RRR value for the inner coil ($\sim 225$) is significantly larger than that of the outer coil ($\sim 95$). This is not necessarily a surprise since the inner and outer cable strands are made from completely different billets. It also interesting to point out that HGQS01 cable RRR value was about 1.6 times lower than HGQS02 cable RRR value. This might be due to a different coil curing process.

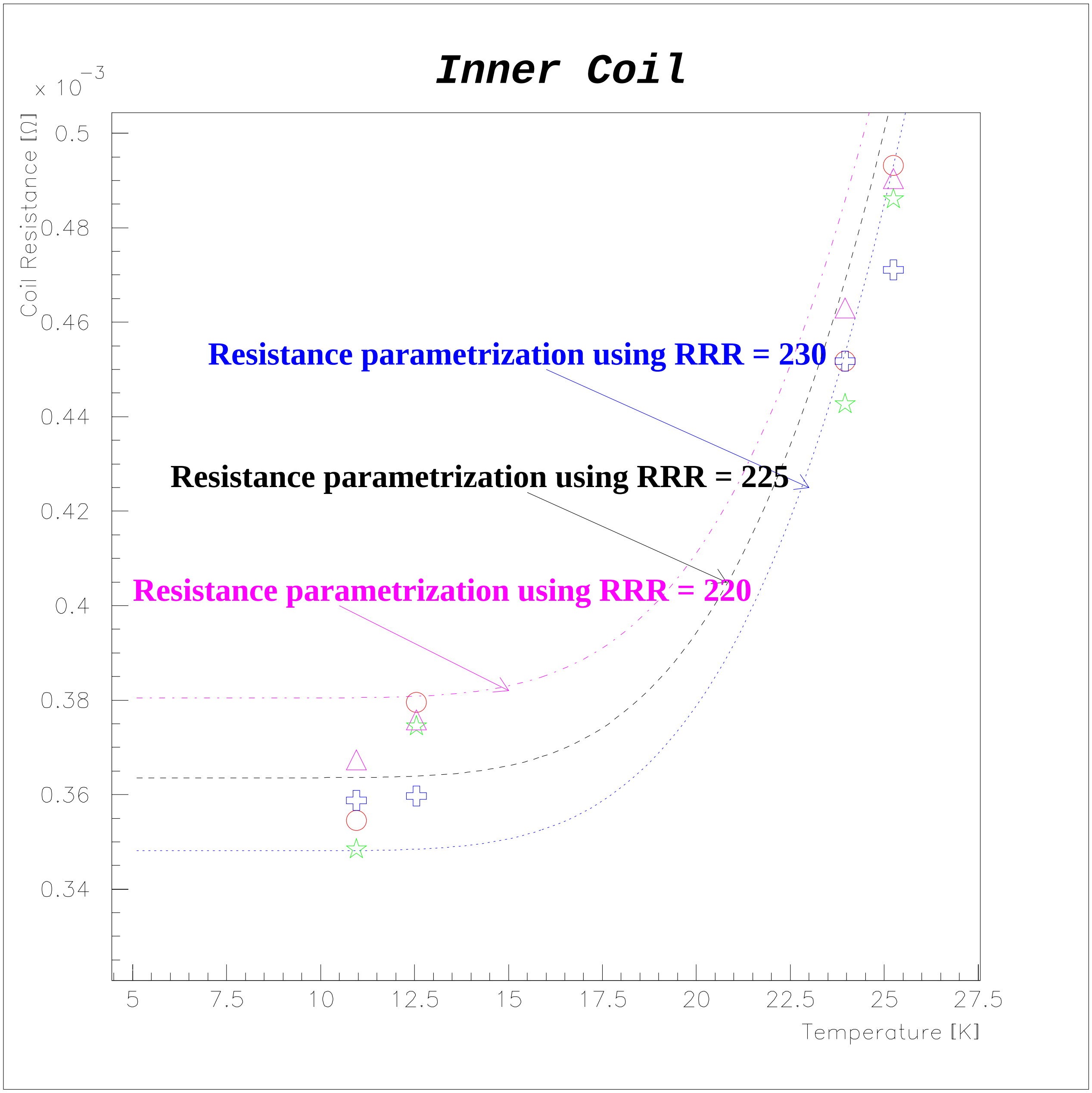


Figure 5.1: Inner coil resistance temperature dependence comparison with parametrization. (rrr1.ps)

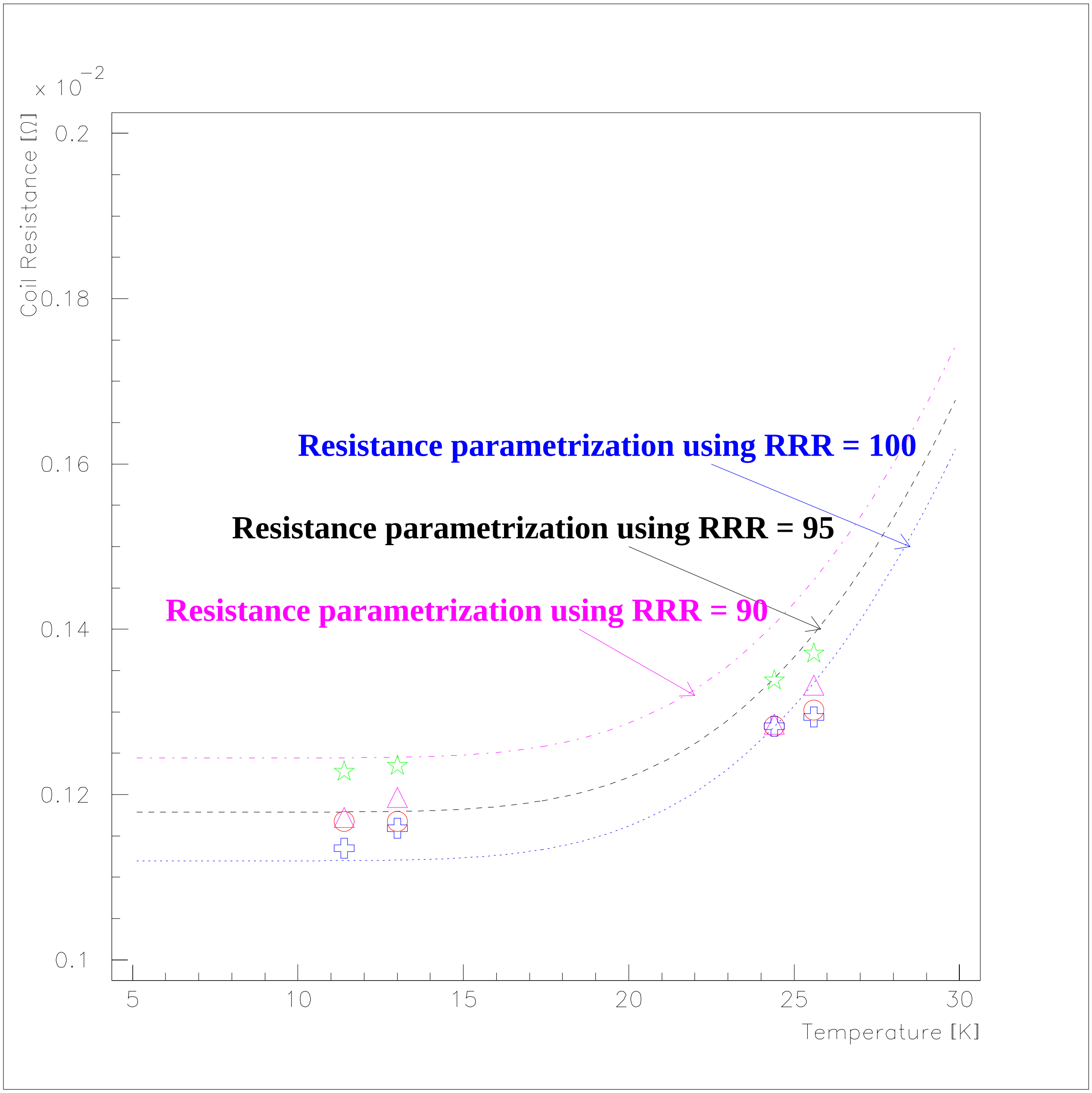


Figure 5.2: Outer coil resistance temperature dependence comparison with parametrization. (rrr2.ps)

# Appendix A

# HGQS01 TEST PLAN

Thermal Cycle I

- Magnetic measurements
- Room Temperature Pretest and Cool down
  RRR
- At 4.5K Operation
  Pre-Current excitation Checkout
  2500 amp Heater test
  Strain gauge runs
  Quench Plateau (max. 5 quenches)
  Ramp Rate Studies
- At 1.9K Operation
  Pre-current excitation Checkout
  3000 amp Heater tests
  Strain gauge runs
  Quench Plateau
  Ramp rate studies
  Magnetic measurements

Heater studies (outer, interlayer, spot heater)
Quench Current vs. temperature
RRR

Thermal Cycle II

- Room Temperature Pretest and Cool down
- At 4.5K Operation
  Pre-Current excitation Checkout
  2500 amp Heater test
  Quench Plateau (max. 5 quenches)
  Ramp Rate Studies
- At 1.9K Operation
  Pre-current excitation Checkout
  3000 amp Heater tests
  Strain gauge runs
  Quench Plateau
  Ramp rate studies
  Heater studies (outer, interlayer, spot heater)
  Energy loss measurement
  Quench Current vs. temperature
  RRR

## A.1 Thermal cycle I

### A.1.1 Magnetic measurements

1. Without Yoke
2. With Yoke

3. In the dewar (optional)
   (a) Locate magnetic center by scanning ends
   (b) Apply ±10 A. Take measurements at 8 different z locations. At each z step make 25 rotations. Take these readings with "amplifiers in".

### A.1.2 Room Temperature Pretest/Cooldown

1. Follow Present procedures for Strain gauge, voltage taps, thermometer, and heater validation. Procedures include:
   (a) Hi pot the magnet in gaseous He environment. Maximum volts should not exceed $V_{max}$ value (to be determined).
   (b) 4 wire measurement of all strain gages
   (c) 5 amps across magnet, measure voltage across taps Measure magnet resistance and compare it to the value measured at IB3. Verify that there are no shorts in the magnet
   (d) 4 wire heater resistance, system resistance for all four heaters.
2. Record at least 10 strain gage readings at room temperature, check values with post assembly readings.
3. Set strain gage and thermometer readings to 10 minute intervals
4. Place 5 amps through magnet, measure voltage across magnet (each eigth coils separately).
5. Cool down to 80K, then change strain gage and thermometer readings to 1 minute intervals. Cool to 4.5 K , 1.1 ATM with unrestricted cooldown following VMTF cool-down procedure and take volage readings for RRR studies ( make sure to get data around ~10 K). Take Strain gauge runs as well. Verify that no shorts appeared during cooldown.

### A.1.3 At 4.5 K Operation

1. Cold electrical tests prior to magnet testing

   (a) Check magnet resistance to ground

   (b) Hi pot (1.1 ATM helium). Maximum volts should not exceed $V_{max}$ value (to be determined).

   (c) Make sure that strain gauge readings are recorded

   (d) Protect magnet with a 60 m$\Omega$ dump resistor. $I_{max} * R_{dump} \leq 1000V$

   (e) Heater Pretests

      i. Configure QLM to fire heater with 1 sec dump firing delay

      ii. Check outer and inter-layer heater and heater system resistance using 4 wire techniques. System capacitance should be set to approximately 14.4 mF.

      iii. Verify that inter-layer and outer heaters are wired in parallel check system continuity

      iv. Fire inter-layer heaters from VMTF prgram. Verify RC, V heaters, I heaters from data logger plots

   (f) Disable Digital QDC (or set to high tresholds)

   (g) Balance quench detection circuitry for analog QDC

      i. Set dump delay to 0 sec

      ii. sawtooth ramps between 50 A and 200 A at 100 A/sec.

      iii. Establish thresholds based on observed noise versus anticipated signals.

   (h) Balance quench detection circuit for DQDC

   (i) Set dump delay to 20 msec and the heater delay to 0msec. Manual trip at 1000 A. **Every single analog QDC platform has to be checked separately. Power supply, dump switch, heater and interlock respond should follow the proper quench logic.** Delay heater firing to 1 sec dump delay = 0 sec. Do another manual trip and check L/R, look at all data logger voltage signals; compare $V_{max}$ to $I * R_{dump}$

2. Quench Heater Protection test
   (a) Set dump resistor delay to 0 ms, no heater delay, no power supply phase off delay
   (b) At 2500A magnet current, determine voltage required to quench heaters with $t_{fn} < 200$ ms
   (c) If MIITS o.k dump delay to 20 ms, delay heater firing to 0 ms
   (d) Check quench logic signal for proper quench timing sequence
3. Strain gauge run
   (a) Dump resistor set to 60 m$\Omega$, 20 ms delay , delay heater to 0 ms, heater value as perr 0.2.3 2.b
   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run "snap-shot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.
      i. Run 1: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 7100 A and from 7100 A to 0 A. Disable "fast strain gauge" script.
      ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 8400 A and from 8400 A to 0 A. Disable "fast strain gauge" script.
      iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9000 A and from 9000 A to 0 A. Disable "fast strain gauge" script. 9000 A
      iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9500 A and from 9500 A to 0 A. Disable "fast strain gauge" script. 9500 A
      v. Run 5: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable "fast strain gauge" script. 10000 A
      vi. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10500 A and from 10500 A to 0 A. Disable "fast strain gauge" script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   Before each quench measure the inductance of the magnet. Make sure that the inductance remain unchanged. With ramp rate = 20 A/sec, train the magnet. Do not do more than 5 quenches. The predicted short sample limit currents (inner coil) is 10340 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 a/s, 150 a/s,

### A.1.4 At 1.9K Operation

1. Cold Electrical tests prior to current excitation Repeat section 0.2.3 1.c,d,e

2. Quench Heater Protection Test Repeat Section 0.2.3 2.a,b,c,d with 3000A applied current.

3. Strain gauge run

   (a) Repeat Section 0.2.2 4.a

   (b) At Ramp rate = 20 A /sec. :

   Measure the inductance of the magnet.Make sure to run "snap-shot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.

      i. Run 1: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable "fast strain gauge" script.

      ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11000 A and from 11000 A to 0 A. Disable "fast strain gauge" script.

      iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11800 A and from 11800 A to 0 A. Disable "fast strain gauge" script.

      iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 12700 A and from 12700 A to 0 A. Disable "fast strain gauge" script.

v. Run 5: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 13400 A and from 13400 A to 0 A. Disable "fast strain gauge" script.

vi. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 14200 A and from 14200 A to 0 A. Disable "fast strain gauge" script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   With ramp rate = 20 A/sec, train the magnet until 4 plateau quenches have occurred. Do not do more than 15 quenches (only if magnet shows interesting behavior). The predicted short sample limit currents (inner coil) is 13900 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 A/sec, 200 A/sec, 150 A/sec, 100 A/sec, 75 A/sec, 50 A/sec

6. Magnetic measurements

   The default ramp rate is 20 A/sec.

   The nominal data set is 25 rotations of the coil.

   All measurement sequences should begin with a "cleansing" quench at $\sim$ 10000A. A cleansing quench is done by firing the magnet heaters with magnet current high enough to produce a small remnant field.

   (a) Set the heater delay to 0 sec, dump delay to 20 msec, and dump resistance to 60 m$\Omega$.

   (b) Determine the minimum magnet current for a cleansing quench: check the effect of a cleansing quench at 10000 A by checking the remnant magnetic field. If the remnant field is substantial increase the current and quench the magnet again. Repeat this proceedure until the minimum current is found. Use this value of the current for all cleasing quenches needed for this test plan.

   (c) Remove pre-amplifiers used for warm measurement if this has not already been done.

(d) Set magnet measurement coordinate system as per TD-98-xxx. File the completed note with this run plan.

(e) Z scans: take measurements at 8 different z locations along the length of the cold mass.

  i. Make Z scan at 2000 A

    A. Estimate magnet center and compare to the predicted value.

  ii. Make Z scan at 6000 A

  iii. Make Z scan at $I_{quench} - 500$ A

(f) End scans (lead end): move the probe by 2 cm increments and at each step take a measurement. Begin outside of the magnet. Make sure to cover $\pm 30$ cm of the end region (at least 30 z positions).

  i. Make end scan at 2000 A

  ii. Make end scan at $I_{quench} - 500$ A

(g) Make a "hysteresis loop" measurement at magnet center (t.b.d.): make three consecutive loops from $I_{min}$ to $I_{quench} - 500$ A with continuous measurement. We define $I_{min}$ as a current near to the injection current; $I_{quench}$ is the quench plateau current reached following training .

(h) Make a standardization cycle (see Fig. ??) measurement: ramp to flattop current, $I_{plateau} = I_{quench} - 500$ A, dwell at $I_{plateau}$ for $t_{dwell}$ ramp down to 50 A, dwell for 2 sec, ramp to 800 A; wait $t_{injection}$, then ramp to $I_{quench} - 500$ A at 20 A/sec.

  Default parameters are $I_{plateau} = I_{quench} - 500$ A; $t_{dwell} = 30$ min.; $t_{injection} = 30$ min.

(i) Analyze the data from the standardization cycle measurement. If "dynamic effects" are seen in the data, the following measurements will be made. (Wait to perform these measurements UNTIL the data have been analyzed, if necessary, continuing the measurement program with item (j).)

  i. Repeat the standardization cycle with different $I_{plateau}$. The other parameters remain the same.

  ii. Repeat the standardization cycle with yet a different $I_{plateau}$. The other parameters remain the same.

iii. Pick an $I_{plateau}$ from the above list and repeat the standardization cycle with a different $t_{dwell}$.

iv. Pick an $I_{plateau}$ from the above list and repeat the standardization cycle with a different $t_{injection}$.

(j) DC loop ("stairstep" loop): Take continuous measurements during the loop. Stop for 2 min. at each of the following currents: 0, 1000, 2000, 3000, 4000, 5000, 6000, ... $I_{quench} - 500$ A on both the up ramp and down ramp.

(k) Repeat the hysteresis loop of (g) with different ramp rates: 10 A/sec, 40 A/sec, 80 A/sec.

(l) Repeat the hysteresis loop of (g) at 2 different z positions (t.b.d.)

7. Heater studies at 1.9K

(a) Set dump resistor delay to 20 ms, no heater delay, no power supply phase off delay or delay it within MIITs limit (12 MIITs)

(b) Outer Heater study

i. At $I/I_c = 0.2$ magnet current determine Vmin for quench. Fire heaters at additional voltage values:
225, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

ii. $I/I_c = 0.4$ determine Vmin for quench.
200, 250, 300, 400 . DO NOT EXCEDE MAXIMUM HFU VOLTAGE

iii. $I/I_c = 0.7$ determine Vmin for quench.
110, 150, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

iv. $I/I_c = 0.9$ determine Vmin for quench Fire heaters at additional voltage values:
90, 150, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

(c) Interlayer heater study. Repeat outer heater study.

(d) Spot heater study

i. At $I/I_c = 0.2$ magnet current determine Vmin for quench.

   ii. $I/I_c = 0.4$ determine Vmin for quench.
   iii. $I/I_c = 0.7$ determine Vmin for quench.
   iv. $I/I_c = 0.9$ determine Vmin for quench.

(e) Quench Current vs. temperature
Ramp magnet to quench at 20 a/s at the following temperatures
1.8K, 2.1K, 2.7K, 3.2K, 3.7K, 4.2K
should not be exact value ( $\pm 0.2$ K)

(f) RRR measurement
Perform 4 wire measurement using DMM. The applied current should be 5amps and applied only during data taking. Take reading in every couple hours, however make sure that there is a measurement taken when the magnet temperature is between 15 - 20 K.

## A.2 Thermal cycle II

### A.2.1 Room Temperature Pretest/Cooldown

1. Follow Present procedures for Strain gauge, voltage taps, thermometer, and heater validation. Procedures include:
   (a) Hi pot the magnet in gaseous He environment. Maximum volts should not exceed $V_{max}$ value (to be determined).
   (b) 4 wire measurement of all strain gages
   (c) 5 amps across magnet, measure voltage across taps Measure magnet resistance and compare it to the value measured at IB3. Verify that there are no shorts in the magnet
   (d) 4 wire heater resistance, system resistance for all four heaters.
2. Record at least 10 strain gage readings at room temperature, check values with thermal cycle I readings.
3. Set strain gage and thermometer readings to 10 minute intervals
4. Verify that no shorts appeared during cooldown.

### A.2.2 At 4.5 K Operation

1. Cold electrical tests prior to magnet testing

   (a) Check magnet resistance to ground

   (b) Hi pot (1.1 ATM helium). Maximum volts should not exceed $V_{max}$ value (to be determined).

   (c) Make sure that strain gauge readings are recorded

   (d) Protect magnet with a 60 m$\Omega$ dump resistor. $I_{max} * R_{dump} \leq 1000V$

   (e) Heater Pretests

      i. Configure QLM to fire heater with 25 msec dump firing delay

      ii. Check outer and inter-layer heater and heater system resistance using 4 wire techniques. System capacitance should be set to approximately 14.4 mF.

      iii. Verify that inter-layer and outer heaters are wired in parallel check system continuity

      iv. Fire inter-layer heaters from VMTF prgram. Verify RC, V heaters, I heaters from data logger plots

   (f) Disable Digital QDC (or set to high tresholds)

   (g) Balance quench detection circuitry for analog QDC

      i. Set dump delay to 0 sec

      ii. sawtooth ramps between 50 A and 200 A at 100 A/sec.

      iii. sawtooth ramps between 50 A and 400 A at 300 A/sec.

      iv. Establish thresholds based on observed noise versus anticipated signals.

   (h) Balance quench detection circuit for DQDC

   (i) Set dump delay to 25 msec and the heater delay to 0msec. Manual trip at 1000 A. **Every single analog QDC platform has to be checked separately. Power supply, dump switch, heater and interlock respond should follow the proper quench logic.** Delay heater firing to 1 sec dump delay = 0 sec. Do another manual trip and check L/R, look at all data logger voltage signals; compare $V_{max}$ to $I * R_{dump}$

2. Quench Heater Protection test

   (a) Set dump resistor delay to 25 ms, no heater delay, no power supply phase off delay

   (b) At 2500A magnet current, determine voltage required to quench heaters with $t_{fn} < 200$ ms

   (c) If MIITS o.k dump delay to 25 ms, delay heater firing to 20 ms

   (d) Check quench logic signal for proper quench timing sequence

3. Strain gauge run

   (a) Dump resistor set to 60 m$\Omega$, 25 ms delay , delay heater to 20 ms, heater value as perr 0.2.3 2.b

   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run “snapshot” script. Take strain gauge runs, one file per current loop, using the sequences of currents below.

      i. Run 1: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 7100 A and from 7100 A to 0 A. Disable “fast strain gauge” script.

      ii. Run 2: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 8400 A and from 8400 A to 0 A. Disable “fast strain gauge” script.

      iii. Run 3: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9000 A and from 9000 A to 0 A. Disable “fast strain gauge” script. 9000 A

      iv. Run 4: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9500 A and from 9500 A to 0 A. Disable “fast strain gauge” script. 9500 A

      v. Run 5: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable “fast strain gauge” script. 10000 A

      vi. Run 4: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10500 A and from 10500 A to 0 A. Disable “fast strain gauge” script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   Before each quench measure the inductance of the magnet. Make sure that the inductance remain unchanged. With ramp rate = 20 A/sec, train the magnet. Do not do more than 5 quenches. The predicted short sample limit currents (inner coil) is 10340 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 a/s, 150 a/s,

### A.2.3 At 1.9K Operation

1. Cold Electrical tests prior to current excitation Repeat section 0.2.3 1.c,d,e

2. Quench Heater Protection Test Repeat Section 0.2.3 2.a,b,c,d with 3000A applied current.

3. Strain gauge run

   (a) Repeat Section 0.2.2 4.a

   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run "snap-shot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.

      i. Run 1: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable "fast strain gauge" script.

      ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11000 A and from 11000 A to 0 A. Disable "fast strain gauge" script.

      iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11800 A and from 11800 A to 0 A. Disable "fast strain gauge" script.

      iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 12700 A and from 12700 A to 0 A. Disable "fast strain gauge" script.

v. Run 5: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 13400 A and from 13400 A to 0 A. Disable "fast strain gauge" script.

vi. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 14200 A and from 14200 A to 0 A. Disable "fast strain gauge" script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   With ramp rate = 20 A/sec, train the magnet until 4 plateau quenches have occurred. Do not do more than 15 quenches (only if magnet shows interesting behavior). The predicted short sample limit currents (inner coil) is 13900 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to $I_{plateau} - 100A$, and from $I_{plateau} - 100A$ to 0 A. Disable "fast strain gauge" script.

6. RAMP RATE dependence studies.

   Ramp to quench at 300 A/sec, 200 A/sec, 150 A/sec, 100 A/sec, 75 A/sec, 50 A/sec

7. Heater studies at 1.9K

   (a) Set dump resistor delay to 25 ms, no heater delay, no power supply phase off delay or delay it within MIITs limit (12 MIITs)

   (b) Outer Heater study

      i. At $I/I_c = 0.2$ magnet current determine Vmin for quench. Fire heaters at additional voltage values:
      225, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

      ii. $I/I_c = 0.4$ determine Vmin for quench.
      200, 250, 300, 400 . DO NOT EXCEDE MAXIMUM HFU VOLTAGE

iii. $I/I_c = 0.7$ determine Vmin for quench.
110, 150, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

iv. $I/I_c = 0.9$ determine Vmin for quench Fire heaters at additional voltage values:
90, 150, 250, 300, 400. DO NOT EXCEDE MAXIMUM HFU VOLTAGE

(c) Interlayer heater study. Repeat outer heater study.

(d) Spot heater study

i. For protection use interlayer heaters. Set SHFU=400V and 0msec delay. At $I/I_c = 0.9$ fire the outer spot heater with the following Dump delays:
30 msec, 40 msec, 50 msec, 60 msec

ii. Repeat the above with I = 10000 A.
Make sure the quench integral value is within the 15 MIITs limit!

8. If time permits: Energy loss measurement (at 1.9K) Ramp the magnet up to 10000A from 500A wait 5 sec then ramp down. Repeat this at least three times. Monitor coil voltages.

   Change the ramp rate between 30 - 300 A/s ( 30A/s, 50 A/s, 100 A/s, 150 A/s, 200 A/s, 250 A/s, 300 A/s)

9. Quench Current vs. temperature

   Ramp magnet to quench at 20 a/s at the following temperatures

   1.8K, 2.1K, 2.7K, 3.2K, 3.7K, 4.2K

   should not be exact value ( $\pm 0.2$ K)

10. RRR measurement

    Perform 4 wire measurement using DMM. The applied current should be 5amps and applied only during data taking. Take reading in every couple hours, however make sure that there is a measurement taken when the magnet temperature is between 15 - 20 K.